Evapotranspiration of Full-, Deficit-Irrigated, and Dryland Cotton on the Northern Texas High Plains

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Abstract: Cotton (*Gossypium hirsutum* L.) is beginning to be produced on the Northern Texas High Plains as a lower water-requiring crop while producing an acceptable profit. Cotton is a warm season, perennial species produced like an annual yet it requires a delicate balance of water and water deficit controls to most effectively produce high yields in this thermally limited environment. This study measured the water use of cotton in fully irrigated, deficiently irrigated, and dryland regimes in a Northern Texas High Plains environment using precision weighing lysimeters in 2000 and 2001. A lateral-move sprinkler system was used to irrigate the fields. The water use data were used to develop crop coefficient data and compared with the FAO-56 method for estimating crop water use. Cotton yield, water use, and water use efficiency was found to be as good in this region as other more noted cotton regions. FAO-56 evapotranspiration prediction procedures performed better for the more fully irrigated treatments in this environment.

CE Database subject headings: Crops; Crop yield; Evapotranspiration; Soil water; Texas; Agriculture.

Introduction

Irrigation supplies from the northern High Plains Aquifer (Ogallala Aquifer) are declining due to water mining and the limited aquifer recharge. Producers are seeking alternate crops in the northern portion of the Southern High Plains that might reduce water consumption and extend the aquifer's useful life. Corn (*Zea mays* L.) is widely produced in the region with exceptionally high yields (USDA-NASS 2001), but it has a large irrigation requirement (Howell et al. 1997). Cotton (*Gossypium hirsutum* L.) offers potentially equal gross income while requiring less irrigation water and the ability to be produced under dryland conditions while corn is not a reliable dryland crop in this region. The Northern Texas High Plains is adjacent to the largest contiguous cotton-producing region in the U.S., but it has a growing season length and thermal environment that is marginal for cotton. Nevertheless, producers are moving cotton production farther north in search of an alternate, economical crop. This region is far from ideal for cotton (Peng et al. 1989) with its short season, cool temperatures, high evaporative demand, and water scarcity (both from irrigation and growing season rainfall).

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Food and Agricultural Organization (FAO)-56 evapotranspiration (ET) methods (Allen et al. 1998) replaced the FAO-24 (Doorenbos and Pruitt 1975) methods for estimating crop water use and proposed using the dual crop coefficient approach based on Wright (1982), but FAO-56 used more precise definitions for the separation of soil water evaporation and crop transpiration from the lumped crop evapotranspiration and used the "straight-line" crop coefficient (K_c) approach from FAO-24. Both FAO-56 and FAO-24 are based on "grass reference" ET (termed ET_0) with FAO-24 being based on a Penman equation and FAO-56 being based on the Penman–Monteith (PM) equation for a specified grass height (0.12 m), surface resistance (70 s m^{-1}), albedo (0.23), and constant latent heat flux (2.45 MJ kg^{-1}). These ET methods are intended to improve irrigation scheduling programs such as Jensen et al. (1970, 1971). Although several methods are employed to express the time base for K_c curves, FAO-56 used a day scale while others have used a thermal scale based on growing degree days (GDD) (Sammis et al. 1985; Stegman 1988; Ayars and Hutmacher 1994; Slack et al. 1996; and Hunsaker 1999). The GDD scale has been reported to improve intersite and interseasonal transferability of K_c curves. Methods for computing GDDs differ significantly, including time base (hour or shorter to daily values), methods for computing the GDDs (Fry 1983), and varying base and upper threshold temperatures used.

Hunsaker (1999) developed K_c curves for a short-season cotton variety in Arizona based on the California Irrigation Management Information System (CIMIS) hourly Penman equation (Snyder and Pruitt 1985) for both the FAO-56 "straight line" and GDD based K_c methods. Their K_c values were larger than those proposed in FAO-56 for cotton. Allen (1999) applied the FAO-56 procedures to a large irrigation district in the western U.S., and he found an 8% overestimate, which he attributed to actual crop conditions not fully representing the more "pristine" conditions assumed in FAO-56. Tolk and Howell (2001) found the dual K_c approach for sorghum [*Sorghum bicolor* (L.) Moench] superior compared with the single K_c approach using the FAO-56 methodology. The FAO-56 soil water evaporation procedures tended to overestimate evaporation early in the season, and the "straight

Table 1. Agronomic and Management Information

Category	2000 Irrigated	2000 Dryland	2001 Irrigated	2001 Dryland
Apply herbicide	April 27	April 26	April 27	April 30
Plant	May 17	May 16	May 16	May 17
Emergence	May 26	May 28	May 28	May 29
Installed neutron tubes	May 31	June 1	May 29	May 29
Cultivate	July 6	July 10	NA	NA
Furrow dike installation	July 7	NA	NA	NA
Begin deficit treatment	July 26	NA	July 2	NA
Harvest	November 14	October 18	October 30	October 22

Note: NA = not applicable.

line'' water limits on ET (based on Kerr et al. 1993) tended to overestimate simulated effects on ET, particularly at the end of the season. Grismer (2002) reported that cotton K_c values that were measured in Arizona and California exceeded those reported in FAO-56 by 30–35% under nonwater-stressed conditions, by 30% in California under water stress, and by 20–25% in desert environments in Arizona and California.

Few studies besides Allen (1999, 2000) and Tolk and Howell (2001) have evaluated the FAO-56 methods independently. The purpose of this paper is to report cotton water use amounts and rates in an environment not optimum for cotton and to compare the resulting water use rates in terms of the FAO-56 dual K_c approach across three water regimes.

Materials and Methods

Agronomy and Treatments

The study was conducted at the USDA-ARS Laboratory at Bushland, Tex. (35° 11′ N lat.; 102° 06′ W long.; 1,170 m elevation above mean sea level). ET was measured during the 2000 and 2001 seasons with two weighing lysimeters (Marek et al. 1988) each located in the center of 4.4-ha 210 m E-W by 210 m N-S fields (four fields arranged in a square pattern). Weighting lysimeters offer one of the most accurate means to measure ET (Hatfield 1990). Predominate wind direction is SW to SSW, and the unobstructed fetch (fallow fields or dryland cropped areas) in this direction exceeds 1 km.

The soil at this site is classified as Pullman clay loam (fine, mixed, superactive thermic Torrertic Paleustoll) (Taylor et al. 1963; Unger and Pringle 1981) which is described as slowly permeable because of a dense Bt horizon about 0.3–0.5 m below the surface. The plant available water holding capacity within the top 2.0 m of the profile is approximately 240 mm (~200 mm to 1.5 m depth). A calcareous layer at about the 1.5 m depth limits significant rooting and water extraction below this depth. This soil is common to more than 1.2 million ha of land in this region and about 1/3 of the sprinkler-irrigated area in the Texas High Plains (Musick et al. 1988). The field slope is less than 0.3%.

Two adjacent lysimeter fields (designated west and east) each containing two weighing lysimeters (designated NW & SW and NE & SE, respectively) were planted to cotton (Paymaster 2145) in each season. (The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by the USDA-Agricultural Research Service.) Each lysimeter field with its two subfields contained a weighing lysimeter in its center (Marek et al. 1988). Both

lysimeter fields were planted to the same variety (Paymaster 2145) and managed similarly. The west lysimeter field was dryland (DRY) with the north half (NW) in 0.76-m rows and the south half (SW) in 0.25-m rows in 2000 and twin rows 0.25 m apart on a 0.76-m center spacing in 2001. The NW field was sown at a rate of 17 seeds m^{-2} (13 seeds per meter of row). Data from the SW field are not being used in this study (i.e., only the data from cotton fields with 0.76-m spaced rows are being used herein). In the east lysimeter field (SE and NE fields), rows were on raised beds and the furrows were diked to store irrigation and rainfall. In the NW field, rows were flat without beds or dikes. The sowing rate was the same for the FULL and DEFICIT treatment at 21 seeds m^{-2} (16 seeds per meter of row) in 2000, but it was reduced slightly to 20 seeds m^{-2} (15 seeds per meter of row) in 2001. The lysimeters were sown at a thicker rate and hand thinned about 2 weeks after emergence to match field plant densities.

Table 1 summarizes the agronomic and management details. All field operations were performed with standard 4.6-m row-crop field equipment, except in the immediate 30-m^2 area at each lysimeter where hand-cultural methods were required. Fertility and pest control were applied uniformly to the field area.

Irrigations

The east lysimeter field was irrigated in both years with the south half (SE) being irrigated to meet the crop water use (FULL) but allowed to reach boll cutout and dry down for maturity. The north half (NE) was irrigated at one-half the FULL rate, except for a few initial irrigations for establishment at the FULL rate, on the same days by using smaller sized nozzles on the irrigation spray heads to achieve approximately one-half the flow rate (i.e., one-half the peak application rate and one-half the application amount). The FULL treatment was managed to not completely meet the ''potential'' water demand late in the season to reduce vegetative growth in favor of boll filling and eventual opening of the bolls likely to mature by the end of the season (a killing frost). Irrigations were applied with a 10-span lateral-move sprinkler system (Lindsay Manufacturing, Omaha, Neb.) with an end-feed hose and aboveground, end guidance cable. The sprinkler system was aligned N-S, and irrigated E-W or W-E. The system was equipped with gooseneck fittings and spray heads (Nelson D3000, Nelson Irrigation, Walla Walla, Wash.) with medium grooved, concaved spray plates on drops located about 1.5 m above the ground and 1.52 m apart. Each spray head was equipped with a 100-kPa pressure regulator and a 1-kg polyethylene drop weight. Irrigations were scheduled to meet the ET water use rate and were typically applied in one to two 25-mm applications per week.

Irrigations were managed on the FULL treatment to minimize early water deficits with the available irrigation capacity while allowing the soil water profile to deplete in order to initiate boll cutout and to use the readily available soil water by maturity or just before frost.

Plant and Yield Sampling

Plant samples from 1.0 to 1.5-m^2 areas were obtained periodically to measure crop development. These field samples were taken at sites about 10–20 m away from the lysimeters in areas of the field representative of the lysimeter vegetation. Leaf area index (LAI), crop height (CH), and aboveground dry matter (DM) were measured from three samples. Final yield was measured by harvesting all the open bolls and aboveground plant matter from each lysimeter (9 m^2), and dry matter and yield at harvest were measured from adjacent plant samples. The seed cotton was ginned on a small research gin at the Texas Agricultural Experiment Station at Lubbock and fiber samples were analyzed by the Texas Tech University International Textile Center (data not reported here).

Lysimeter Measurements

Lysimeter mass was determined using a CR-7X data logger (Campbell Scientific, Inc., Logan, Utah). The CR-7X data logger was used to measure and record the lysimeter load cell (SM-50, Interface Inc., Scottsdale, Ariz.) signal at 0.5-Hz (2 s) frequency. The load cell signal was averaged for 5 min and composited to 30-min means (reported on the midpoint of the 30 min, i.e., data were averaged from 0 to 30 min and reported at 15 min), and the lysimeter mass resolution was 0.01 mm, and its accuracy exceeded 0.05 mm (Howell et al. 1995a). Daily ET was determined as the difference between lysimeter mass losses (from evaporation and transpiration) and lysimeter mass gains (from irrigation, precipitation, or dew) divided by the lysimeter area (9 m^2). A pump regulated to -10 kPa provided vacuum drainage, and the drainage effluent was held in two tanks suspended from the lysimeter (their mass was part of the total lysimeter mass) and independently weighed by load cells (drainage rate data are not reported here). ET for each 24-h period was divided by 1.02 to adjust the lysimeter area to the midpoint between the two walls (10 mm air gap; 9.5 mm wall thickness; 9.18 m^2 area instead of the 9.00 m^2 lysimeter surface area). This correction would be applicable for full-cover crops, but it would not be necessary for bare soil conditions, although the wall-gap area might intercept radiant energy and emit a small amount of short- and long-wave radiation to the lysimeter soil. Nevertheless, the lysimeter "effective area" correction was applied to all data uniformly.

Soil Water Measurements

Soil water contents were measured periodically using a neutron probe (model 503DR Hydroprobe, CPN International, Inc., Martinez, Calif.) at 0.2-m depth increments with 30-s counts. Two access tubes were located in each lysimeter (read to 1.9-m depth) and four tubes were located in the field surrounding each lysimeter (read to 2.3-m depth). The probe was field calibrated for the Pullman soil using a method similar to that described by Evett and Steiner (1995).

Table 2. Pullman Soil Parameters Used with FAO-56 Dual K_c Model (Tolk and Howell 2001); see FAO-56 Manual for Parameter Definitions (Allen et al. 1998)

Parameter	Value and unit
FC	0.33 m m^{-3}
PWP	0.20 m m^{-3}
Z_r	1.5 m
Z_e	0.15 m
TEW	34.5 mm
REW	10 mm
TAW	195 mm
RAW	107 mm
p	0.55 (fraction)

Climatic Data, Reference Evapotranspiration, and Crop Coefficients

Solar radiation, wind speed, air temperature, dew point temperature, relative humidity, precipitation, and barometric pressure were measured at an adjacent weather station (Howell et al. 1995b) with an irrigated grass surface (cool-season lawn mixture containing bluegrass, perennial rye-grass, etc.). Reference ET (ET$_0$) was computed with the FAO-56 equation using the exact formulas in Allen et al. (1998).

The crop ET (ET$_c$ in mm d^{-1}) was computed as

$$ET_c = (K_{cb}K_s + K_e)ET_0 \qquad (1)$$

where $K_{cb} =$ "basal" crop coefficient, $K_s =$ soil water deficit factor, $K_e =$ soil water evaporation factor, and ET$_0 =$ grass reference ET in (mm d^{-1}). Values for K_{cb}, K_s, and K_e were derived following Tolk and Howell (2001) (Table 2) for the Pullman soil and using guides from Allen et al. (1998) in the FAO-56 manual. A spreadsheet similar to one developed for use in Tolk and Howell (2001) and patterned after Appendix 8 in the FAO-56 manual was used to compute crop ET using the input ET$_0$ data and K_c values derived from the measured ET (all based on a timescale with a daily increment).

Growing degree-days were computed as the mean of the daily maximum and minimum air temperatures less the base temperature of 15.6°C (Peng et al. 1989; Hake et al. 1990) that is widely used in the cotton community in the Southern High Plains. This GDD method differs from that used by Hunsaker (1999), and the methods described by Fry (1983), who provided some conversions for differing GDD methods.

Model Performance Evaluation

Tolk and Howell (2001) explained the desirability of the Legates and McCabe (1999) statistical procedure ($E =$ modified coefficient of model efficiency), but both that procedure and the Willmott (1981) method ($D =$ coefficient of agreement) that used the error square terms were included and expressed as follows:

$$E = 1.0 - \frac{\Sigma_{i=1}^{N}|O_i - P_i|}{\Sigma_{i=1}^{N}|O_i - \bar{O}|} \qquad (2)$$

$$D = 1.0 - \frac{\Sigma_{i=1}^{N}(O_i - P_i)^2}{\Sigma_{i=1}^{N}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \qquad (3)$$

where $O =$ observed data, $P =$ model predicted value, and $\bar{O} =$ mean observed data. The mean absolute error (MAE) was also computed as

Table 3. Monthly Climatic Data Summary of Daily Mean Values for 2000 and 2001 Compared with the 20-year Bushland Historical Mean Data

2000

Month	T_{max} (°C)	T_{min} (°C)	T_{dew} (°C)	Rad. (MJ m^{-2} day^{-1})	2-m wind (m s^{-1})	Pressure (kPa)	ET_0 (mm day^{-1})	Rain (mm)
May	29.5	11.0	5.6	26.6	5.1	88.1	8.2	11
June	28.9	16.0	14.2	21.7	5.1	88.4	6.5	97
July	33.2	17.9	14.2	26.1	3.9	88.5	7.7	26
August	33.9	17.3	10.8	24.5	3.6	88.6	7.8	1
September	31.1	12.6	5.2	21.2	3.7	88.5	6.7	0
October	20.7	8.1	6.9	12.3	3.7	88.6	3.1	66
2001								
May	25.4	10.4	10.6	24.3	4.0	88.3	5.4	76
June	32.7	16.0	11.0	27.5	4.3	88.4	8.4	34
July	35.1	19.3	12.7	26.6	3.6	88.5	8.4	4
August	31.9	16.8	13.9	22.1	3.0	88.7	6.2	28
September	29.2	12.4	10.7	20.5	3.4	88.6	5.5	12
October	24.0	5.5	1.9	16.1	4.2	88.5	4.8	2
20-year Bushland Historical Means								
May	25.7	9.6	NA	24.7[a]	4.3[a]	NA	NA	60
June	30.1	14.7		26.3	4.3			76
July	32.3	16.9		25.9	3.7			74
August	31.4	16.4		22.9	3.4			71
September	27.6	11.9		19.3	3.6			56
October	21.8	5.3		15.6	3.8			40

Note: NA=not applicable; T_{min}=minimum temperature; T_{max}=maximum temperature; T_{dew}=dew point temperature; and Rad=radiation (solar).

[a]28-year mean.

[b]12-year mean.

$$MAE = \frac{\Sigma_{i=1}^{N} |O_i - P_i|}{N} \qquad (4)$$

Also, standard statistical parameters—coefficient of determination (r^2), standard deviation, mean, and root mean square error (RMSE)—were used to characterize the data and the FAO-56 model performance.

Results and Discussion

Weather and Climatic Conditions

Both of the growing seasons were drought seasons for Bushland, but they were not atypical of the climatic variations experienced on the Southern Great Plains. The climatic conditions are given in Table 3 for the seasons, and the Bushland historical data are presented for comparison. Mean monthly temperatures were not greatly different from long-term monthly means despite the dry summers. After the slightly larger than normal rain in June of 2000, the growing season was devoid of significant rains until late October, which was too late to help the 2000 crop. The 2001 rainfall was again below normal although early rains in May and June reduced the need for early irrigations. Wind speeds at the 2-m elevation were greater than normal in the early 2000 season. The mean daily FAO-56 reference ET (ET_0) was almost identical in both years, although they had slightly differing temporal trends.

Crop Development

Figs. 1 and 2 illustrate the cotton development in each season, respectively. The 2000 crop was planted following alfalfa (*Medicago sativa* L.), which may have affected the growth and devel-

opment. The alfalfa was plowed out during the 1999 fall and winter. The 2001 FULL treatment achieved a greater LAI, CH, and DM than it did in 2000. However, the DRY and DEFICIT treatments had almost the same growth patterns in both years. These cotton growth patterns are typical for the Texas High Plains, although we expected LAI for the FULL treatment to be more alike the pattern in 2001. The FULL treatment achieved a closed canopy in both seasons; however its canopy was taller in 2001 with significantly greater row width spread (as indicated by the LAI values; see Figs. 1 and 2).

Water Use, Yield, and Water Use Efficiency

The seasonal water use, yield, and lysimeters water use efficiency (WUE) data are presented in Table 4. Grismer (2002) recently reviewed these types of data for cotton, emphasizing Arizona and California locations, but he included studies conducted in cotton regions around the world. Our ET and WUE for the FULL and DEFICIT treatments are similar to his summary. He indicated WUE values of 0.19–0.21 kg m^{-3} required a net irrigation amount (after subtracting rainfall) of about 700 mm in the San Joaquin Valley in California. This is considerably greater than our irrigation requirement for cotton on the Northern Texas High Plains (~500 mm or less depending on rainfall). We attribute this partly to our shorter growing season; however, it is difficult to argue that our ET demand is less than the Central Valley of California or the deserts of Arizona or California with the extreme advection experienced in the Southern High Plains due to high winds, low humidity, relatively clear skies, and the high elevation (low barometric pressure).

Figs. 3(C) and 4(C) present the ET of the FULL treatment in 2000 and 2001, respectively. Measured ET approached 14 mm d^{-1} on a few days in both seasons, but more typical maximum daily ET rates approached 10–12 mm d^{-1} on days without
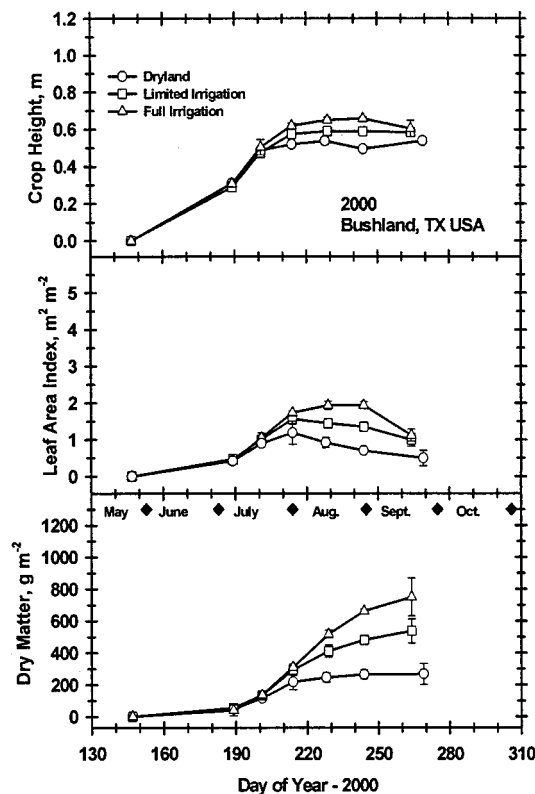
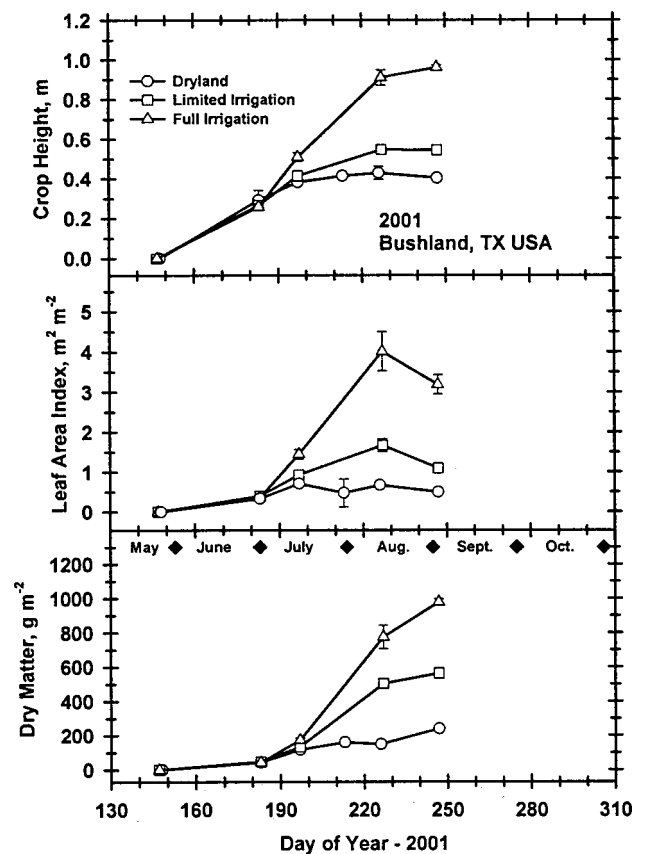**Fig. 1.** Cotton growth parameters in 2000 at Bushland, Tex.

Fig. 2. Cotton growth parameters in 2001 at Bushland, Tex.

strong advection. These maximum ET rates are not greatly different from prior measured maximum daily ET rates for other crops at Bushland (Howell et al. 1995b, 1997). Early season daily ET rates were typically around $1–3$ mm d^{-1}, with values of 6 to 7 mm d^{-1} following an irrigation or large rain event, and appeared to increase more in proportion to crop height than LAI early in the season (before about DOY 200) (Figs. 1 and 2). Irrigation events reached the lysimeter near midday, so maximum daily ET rates would be moderated somewhat for the early season case with mostly bare soil between the day of the irrigation and the following day. Most large summer rain events at Bushland occur during the evening or night from convective thunderstorms, so daily evaporation rates from the soil on the day following the rain may be large, but they could pass from stage I to stage II evaporation in a single day (Allen et al. 1998). Only one daily rainfall

event in both seasons exceeded 50 mm [Figs. 3(A) and 4(A)]. In both seasons, daily ET rates declined almost exponentially with days after DOY 240 (late August; 1 week to 10 days before peak bloom). This decline resulted from the water management strategy to permit root zone soil water depletion to hasten boll maturity, since few cotton blooms after early August will receive enough heat units (GDD) to mature the boll (Peng et al. 1989) in this environment (i.e., the day following the second day of bloom forms the boll; Hake et al. 1990).

In Texas, Wanjura et al. (2002) reported 12 years of drip irrigated cotton yield and irrigation data for Lubbock. They reported stronger correlations between maximum lint yields and cumulative GDD (heat units) than for total water or irrigation applica-

Table 4. Water Use, Yield, and Lysimeters Water Use Data (WUE) Data for 2000 and 2001 Seasons at Bushland, Tex.

| Treatment	2000			2001		
	FULL	DEFICIT	DRY	FULL	DEFICIT	DRY
Parameters						
Measured ET (mm)	775	622	397	739	578	386
FAO-56 Computed ET (mm)	770	619	356	736	639	415
Irrigation (mm)	470	307	12	385	208	14
Rainfall (mm)	201	201	201	214	214	214
Lysimeter yield (g m^{-2})	150.0	89.4	36.4	111.9	126.5	39.7
WUE (kg m^{-3})	0.194	0.144	0.092	0.151	0.219	0.103
Field mean yield (g m^{-2})	131.3	64.6	25.8	102.2	91.9	28.4
Field standard deviation (g m^{-2})	13.3	4.8	3.7	9.6	9.0	21.0
Lysimeter yield within ± 2 standard deviation from the field yield	Yes	No	No	Yes	No	Yes
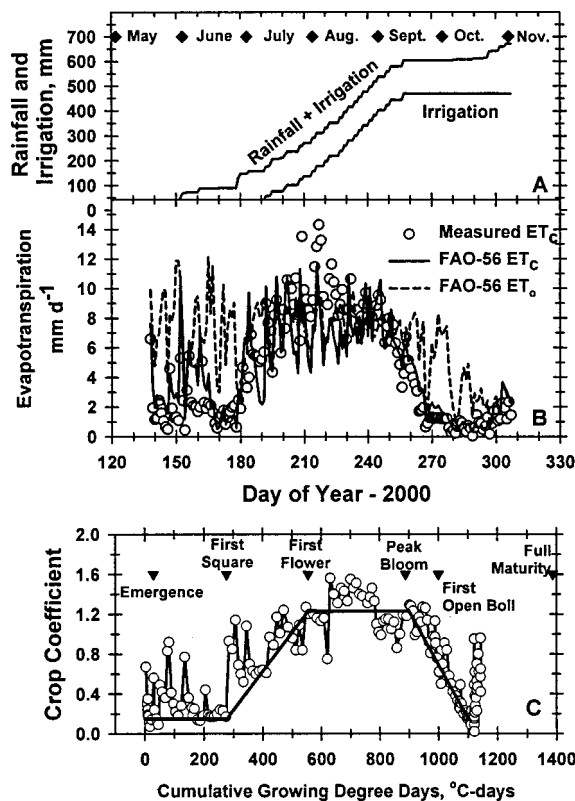
Fig. 3. Cotton water use for full treatment in 2000 at Bushland, Tex. (A) cumulative irrigation and rainfall data; (B) daily evapotranspiration (ET_c) measured and computed by FAO-56 and FAO ET_0 reference ET; and (C) cotton crop coefficient in relation to cumulative GDD for base temperature of 15.6°C.
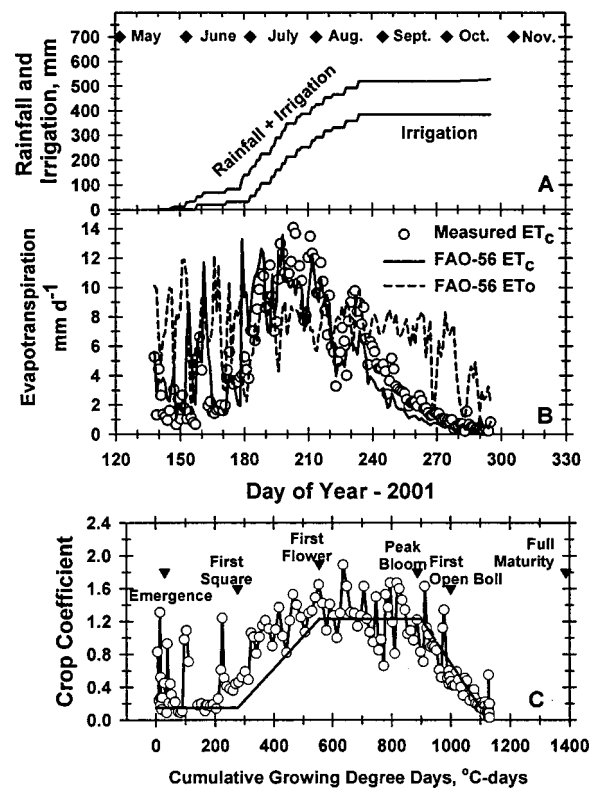

Fig. 4. Cotton water use for full treatment in 2001 at Bushland, Tex. (A) Cumulative irrigation and rainfall data; (B) daily evapotranspiration (ET_c) measured and computed by FAO-56 and FAO ET_0 reference ET; and (C) cotton crop coefficient in relation to cumulative GDD for base temperature of 15.6°C.

tions. Their lint yield response up to maximum yield was approximately 0.114 kg m^{-3} for the irrigation range of 50–540 mm. They had maximum lint yields from 133 to 163 g m^{-2}, which are not greatly different from our higher yields (Table 4) excluding their years affected by adverse weather. They reported a cumulative GDD range from 1092 to 1576°C days. Peng et al. (1989) indicated that, for the Southern Texas High Plains, a heat unit accumulation of approximately 1450°C days with a total water supply rainfall plus irrigation of 550 mm are needed to achieve optimum yields exceeding 70 g m^{-2}. Figs. 3(C) and 4(C) indicated we did not exceed a cumulative GDD of 1130°C days in either season. It is unlikely that a full-season cotton crop can consistently accumulate enough heat units to fully mature all the bolls on the plants in the Northern Texas High Plains environment. It is critical that the first and second position bolls (Hake et al. 1990) be developed by minimizing early crop stresses and that careful insect and disease control measures are utilized to avoid the loss of these primary fruiting positions. Despite the environmental limitations for producing cotton on the Northern Texas High Plains, excellent yield potentials are possible even with DEFICIT irrigations and WUE values exceeding that for many others regions with better environments for cotton (Table 4). Cotton offers regional producers another crop option that has a lower irrigation water requirement yet a high income potential depending on the fiber quality and price.

Fig. 5 presents the relationships between lint yield and ET (A) and WUE and lint yield (B), and the regression results are given in Table 5. The yield and ET relation is similar to that for inland counties in California from Grismer (2002) but markedly different
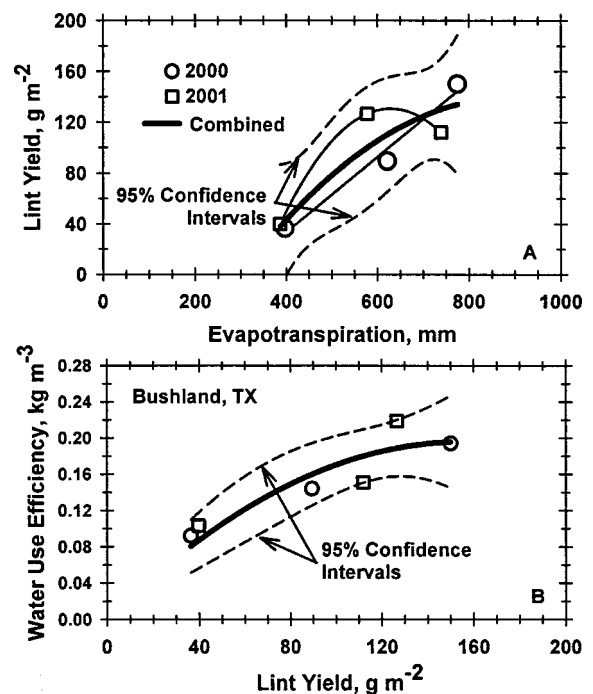

Fig. 5. Cotton lint yield response to evapotranspiration (A, top) and water use efficiency response to lint yield (B, bottom) at Bushland, Tex.

Table 5. Regression Results for Lint Yield (LY) and Evapotranspiration (ET) and Water Use Data (WUE) and Lint Yield for Cotton at Bushland, Tex.

Equation	r^2	$S_{y/x}$ units[a]
2000		
$\quad$ LY $(\text{g cm}^{-2}) = -84.9 + 0.296 \times$ ET (mm)	0.878	11.9
2001		
$\quad$ LY $(\text{g m}^{-2}) = -27.9 + 0.212 \times$ ET (mm)	0.652	38.8
Combined 2000 and 2001		
$\quad$ LY $(\text{g m}^{-2}) = -55.8 + 0.254 \times$ ET (mm)	0.816	22.3
$\quad$ WUE $(\text{kg m}^{-3}) = 0.059 + 9.88 \times 10^{-4} \times$ LY (g m^{-2})	0.855	0.02
$\quad$ LY $(\text{g m}^{-2}) = -174.3 + 0.700 \times$ ET $(\text{mm}) - 3.93 \times 10^{-4} \text{ET}^2$ (mm^2)	0.837	NA
$\quad$ WUE $(\text{kg m}^{-3}) = 0.054 + 6.29 \times 10^{-3} \times$ LY (g m^{-2}) $\quad\quad - 0.932 \times 10^{-7} \times \text{LY}^2$ $(\text{g}^2 \text{ m}^{-4})$	0.855	NA

Note: $S_{y/x}$ = standard error of estimate; and NA = not applicable.

[a] Units are same as dependent variable.

from desert regions in california and Arizona as Grismer (2002) reported. His mean slope (taken as WUE) was 0.19 kg m^{-3}, which does not differ greatly from our mean WUE of 0.18 kg m^{-3} from the DEFICIT and FULL treatments. However, Fig. 5 indicates a significant X-axis intercept exceeding 200 mm before any lint yield was obtained. Also, the two seasons had differing responses for yield to ET for the DEFICIT and FULL treatments not unlike variability as observed by both Grismer (2002) and Wanjura et al. (2002). Cotton water management in a marginal heat unit region (Peng et al. 1989; Wanjura et al. 2002) requires a delicate balance in minimizing crop water deficits while enhancing fruit set, fruit retention, and boll maturity. WUE [Fig. 5(B)] increased substantially with irrigation and the greater lint yields. WUE almost doubled from dryland levels (0.08 kg m^{-3}) to irrigated levels (0.14–0.22 kg m^{-3}) (Table 4). Although Fig. 5 indicates a slight quadratic lint yield response in relation to ET, the quadratic regression was not significantly different ($P < 0.069$) from the linear equation ($P < 0.014$) (Table 5) for the combined seasons. The quadratic response of WUE in relation to lint yield was significantly different ($P < 0.059$) from the linear relationship but not to a major extent ($P < 0.008$ for linear regression). The intercepts for the WUE relationships to lint yield were not significantly different from zero (as should be expected) for both the linear and quadratic regressions.

The FAO-56 model used the computed reference ET$_0$ values [Figs. 3(B) and 4(B)] for the site with the beginning soil water contents matched to the early season measurements. The FAO-56 model fit the FULL treatments [Figs. 3(C) and 4(C)] considerably better than the more water deficit treatments (Table 6). We be-

lieve, without the benefit of a thorough analysis, that the simple "straight line" water stress function, K_s, exaggerated the on-set of ET stress, although we found the "p" value (stress set point) rather insensitive in our case. The soil water stress function is critical in our case because of deficit, declining water supplies, and dryland production. In addition, like Tolk and Howell (2001), we found that the early soil water evaporation was overestimated which caused the simulated and measured ET$_c$ values to depart from synchronization with the FAO-56 model. The index of agreement (D) (Willmott 1981) had higher values than the modified index of model efficiency (E) (Legates and McCabe 1999), which indicated poor model agreement, especially for the DRYLAND treatments. The MAE was 1.14 mm d^{-1} while the RMSE mean was 1.88 mm d^{-1}. Only the FULL treatment ET was fit well by the FAO-56 model.

For the Northern Texas High Plains, Table 7 presents a starting point in the use of FAO-56 methods for cotton in this unusual region for cotton. Figs. 3(A) and 4(A) illustrate the superiority of the GDD basis for crop K_c curves because the GDD scale spreads the critical midseason period while maintaining the needed precision on the season ends. Although we did not present the K_c curves based on a timescale (see Table 7), they required some greater skill in defining the water stress at the end of the midseason and through the late-season periods. The late-season crop coefficients are typically not "adjusted" in FAO-56. But cotton production in this region is often terminated by chemical applications to hasten boll opening and to terminate vegetative growth. Early frost can terminate growth, too, in this region.

Table 6. Model Evaluation Parameters for FAO-56 Procedure for Cotton on Northern Texas High Plains

Treatment	2000			2001		
	FULL	DEFICIT	DRY	FULL	DEFICIT	DRY
Parameters						
D (Willmott 1981)	0.905	0.847	0.817	0.973	0.942	0.873
E (Legates and McCabe 1999)	0.562	0.383	0.095	0.710	0.610	0.390
MAE (mm d^{-1})	1.43	1.31	1.13	0.01	1.43	1.50
RMSE (mm d^{-1})	1.98	1.81	1.44	1.93	2.11	1.99
Mean (mm d^{-1})	4.59	3.71	2.43	4.77	3.68	2.45
Standard deviation (mm d^{-1})	3.66	2.35	1.49	3.82	2.49	1.21
Coefficient of determination, r^2	0.708	0.519	0.432	0.758	0.386	0.078

Note: MAE = mean absolute error; and RMSE = root mean square error.

Table 7. Length of Cotton Growth Stages, K_{cb}, and K_{cb} adjusted Values for Use With FAO-56 Methods for Northern Texas High Plains

Cotton growth stage	Length of stage (days)	Basal crop coefficient (K_{cb})	Adjusted crop coefficient (K_{cb} adj)[a]
Days			
Initial	40–50	0.08	0.15
Development	40	NA	NA
Midseason	50	1.10	1.23
Late-season	28–30	0.15	0.20
GDDs (°C days)			
Initial	0–277	0.08	0.15
Development	277–555	NA	NA
Midseason	555–900	1.10	1.23
Late-season	900–1100	0.15	0.20

Note: NA=not applicable.

[a]Adjustment based on FAO-56 (Allen et al. 1998).

Conclusions

Cotton appears to be a viable alternate crop for the Northern Texas High Plains that can use less water than other crops. The WUE and yield obtained at Bushland rivals those from more noted cotton production regions while offering a crop alternative that responds well to both rainfall and irrigation. The WUE was almost doubled by irrigation. It is noted that these were unusually dry summers.

The FAO-56 ET procedures performed considerably better under the more ''well-watered'' conditions suggesting the need for additional studies on the model's performance or environmental characterization for deficit irrigation and dryland conditions.

Acknowledgments

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